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Liquid absorption and solid adsorption system for household, industrial and automobile applications: A review

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ABSTRACT

The degradation of fossil fuels and other non-renewable energy resources are the challenges faced by current and future generations. This trend requires humans to utilize, reuse, and transform energy efficiently, for the right applications and with the right timing. The low-grade heat from industry, automobiles and the sun could be used/reused to drive a liquid absorption system and solid adsorption system. Then, the absorption and adsorption system could provide refrigeration, dehumidification and heating owing to the proper utilization of low-grade heat at 60–90 °C. The reuse of low-grade heat would reduce the heat pollution to the environment and avoid/minimize the consumption of fossil energy to drive the absorption and adsorption system. In this paper, the absorption and adsorption system are differentiated and categorized by the source of heat energy and its applications. The three main topics discussed are absorption, adsorption, and dehumidification. The individual working mechanism of each absorption and adsorption system is described thoroughly. This paper provides insights into innovative ways for how these systems could be constructed.

Contents

1. Introduction

The main differences between absorption and adsorption are the materials, substance state and circuit layout. In absorption, a base solution dilutes the refrigerant vapor and becomes a weaken solution. The base solution is regenerated by evaporating the refrigerant from the base solution. In adsorption, the refrigerant is adsorbed and refrigerant stays on the surface of the solid-grain adsorber upon cooling. During desorption, the refrigerant evaporates from the solid adsorber material upon heating. For absorption, the adsorber and generator are two different compartments, between which a heat exchanger is always installed. For adsorption, both adsorption and

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desorption share the same adsorber beds. The adsorber beds are heated and cooled in alternative sequence. The similarity between absorption and adsorption is the two-compartment condenser and evaporator. The condenser will condense the refrigerant vapor evaporated during the desorption/regeneration process. The evaporator will evaporate the refrigerant (thus provide cooling effect), and prepare the refrigerant vapor for the adsorption process.

The function of absorption and adsorption system is mainly to provide refrigeration, heat up cold water, and dehumidification. The liquid absorption and solid adsorption system could dehumidify the air when the pairing refrigerant for the system is water vapor in humid air. Sometimes, the same system could provide a cooling effect and dehumidification, as well as heat up cool water.

Both the absorption and adsorption system could reuse the low-grade heat (80–150 °C), such as waste heat from industry, and automobile and solar energy. This would help to reduce the global warming effect by reducing the direct emission of hot gases/air from industry/automobile into the atmosphere. Furthermore, the heat is reused to drive air-conditioning and refrigeration, instead of using electricity or natural resources.

When the heat energy is utilized wisely, it is absorbed from wherever heat is not desired, and pumped to wherever heat is required. The waste heat from industry, households and automobiles can be recycled for absorption refrigeration, adsorption refrigeration, and dehumidification purposes. Renewable energy, such as solar energy, could also drive absorption and adsorption refrigeration systems. This would reduce global dependence on non-renewable energies, such as petroleum and natural gas.

There are several review paper written on absorption, adsorption, and dehumidification. However, there are limited papers which reviewed all three topics concurrently, and categorized them according to different heat sources and applications. When absorption, adsorption and dehumidification are studied together, it will prevent confusion among the systems, and all the system will be defined clearly and precisely.

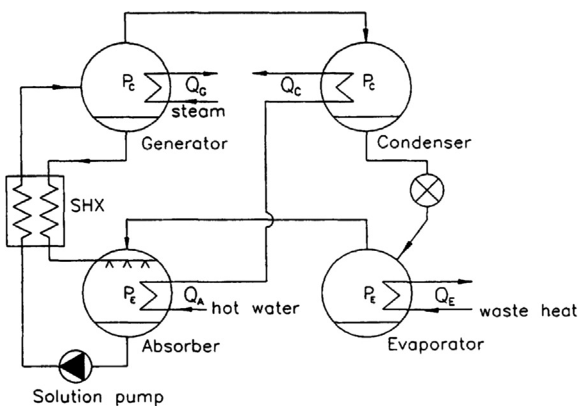

Fig. 1. General layout of absorption system [1].

2. Absorption

In an absorption system, there is one loop for strong solutions and weak solutions (after the refrigerant is diluted in the base solution). There is another loop solely for refrigerant. The strong solution becomes a weak solution after it absorbs the refrigerant from the evaporator. The weak solution becomes a strong solution after it evaporates the refrigerant from base solution and condenses in condenser, after being heated up in a generator. Fig. 1 displays the general layout of an absorption system. Normally, waste heat emitted by industry and automobiles, or from other renewable energy (low-grade heat source), is utilized to operate the generator. Cool water is pumped to cool down the absorber and the condenser (in other words, the adsorber and condenser heat up cool water for household usage). Lastly, the evaporator absorbs unwanted heat to make the absorption cycle function well (evaporator provides chilling effect). In short, a heat pump delivers heat to wherever it is required, and absorbs heat from wherever it is not required.

2.1. Absorption system driven by industrial waste heat

In an absorption system, waste heat and renewable energy could drive the generator, and provide a cooling effect in an

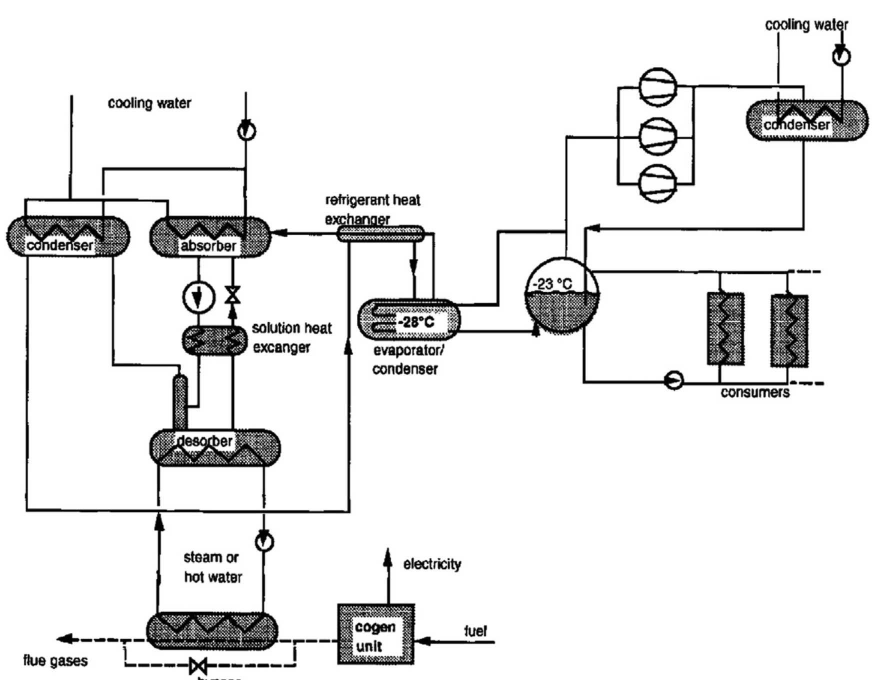

Fig. 2. Combination of am absorption refrigeration plant (ARP) and a compression refrigeration plant [3].

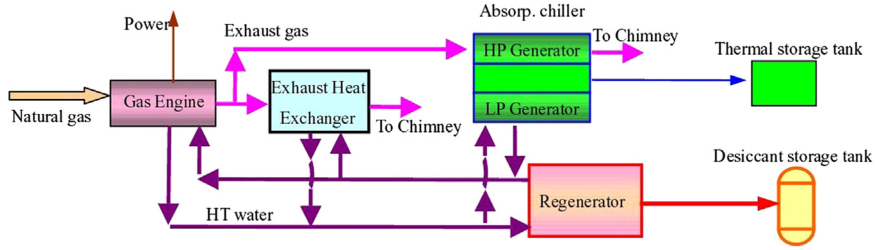

Fig. 3. Absorption chiller driven by exhaust gas and hot coolant from a gas engine [5].

evaporator. The generator and evaporator remove undesirable/waste heat from the space or engine, while the heat released during the absorption and condensation processes could be used for the preparation of hot water. The heat from condensation and absorption might also be thrown out via a cooling tower, in order to recirculate cool water again for the condenser and adsorber.

Jeong et al. [1] recovered waste heat (30–40 °C) from chemical plants to operate the evaporator in their absorption system. The absorption system in Fig. 1 illustrates how the liquid absorbent (LiBr) absorbs refrigerants (water vapor) from the evaporator, and releases heat (Q_a) to hot water. The absorbent becomes a weak solution until it is generated by driving steam (110 °C) in the generator. The absorbent absorbs heat, releases the water vapor, and become a weak solution again. The water vapor is then condensed in the condenser by releasing heat (Q_c) into hot water. The hot water is heated from 30 °C to 60 °C, after it flows through the absorber and the condenser. The heat exchanger (between the generator and the absorber) can preheat the strong solution for the generator, and precool the weak solution for the absorber. Jeong et al. [1] established a numerical model to study the effects of steam temperature, hot water and waste water temperatures, mass flow rate of hot water and waste water, heat transfer area, and the solution circulation rate towards COP $((Q_c+Q_a)/Q_g)$.

Ma et al. [2] recovered waste heat from a synthetic rubber plant, to drive the generator and evaporator. In the absorption heat transformer (AHT), the steam stripping vapor from rubber plant flows through the evaporator to evaporate the water for the absorber (LiBr), and flows through the generator to regenerate the weak solution. During the absorption stage, the absorber absorbs the water from the evaporator, and releases heat to heat up the hot water from 95 °C to 110 °C. Bassols et al. [3] utilized excess steam from electricity generation, to produce 1400 KW of refrigeration at 23 °C. The excess steam drives the desorber/generator. An absorption refrigeration plant (ARP) and compression refrigeration plant (CRP) working together can provide a total of 4900 KW of refrigeration for a margarine factory. In the evaporator for an ARP/condenser for CRP, the ammonia gas evaporates on one side, while the ammonia liquid condenses on the other side (see Fig. 2).

Bruno et al. [4] utilized post-combustion gas from a micro-gas turbine (MGT) and natural gas to direct-fire the chiller at a temperature of 6.7 °C. In the meantime, the exhaust gas and hot water drove the generator of the absorption chiller. The inlet and outlet temperature of the exhaust gases are 170 °C and 100 °C, respectively. The inlet and outlet temperature of hot water are 93 °C and 87.7 °C, respectively. Liu et al. [5] utilized the exhaust gas from a gas engine to drive a high pressure generator of an absorption chiller. In order to drive a low-pressure generator, they made use of exhaust gas to heat up hot water in an exhaust heat exchanger and made use of hot engine-jacket water from the gas engine to generate the adsorption system. Furthermore, the hot water was also utilized to regenerate the liquid desiccant, which was stored in a desiccant storage tank as a concentrated solution (see Fig. 3).

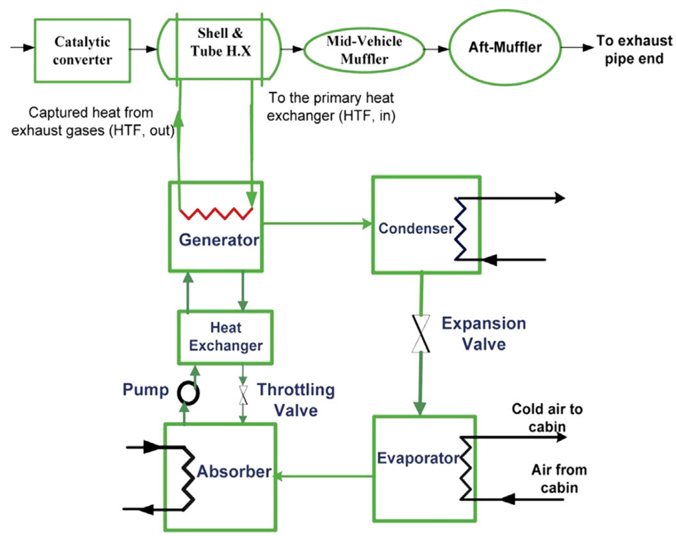

Fig. 4. Absorption system driven by automobile exhaust, for cabin cooling [7].

Liao et al. [6] published their research about crystallization control methods for an integrated absorption and power system. The exhaust gas from a power plant is used to drive the generator, while the exhaust gas from the chiller is recycled to regenerate the desiccant wheel. In order to prevent the crystallization of the strong solution before it enters the absorber, the authors increased the chiller temperature when the absorber temperature or heat sink temperature increased. The authors also recommend controlling the exhaust gas temperature from being too high (which drives the desorber), to prevent crystallization.

2.2. Absorption system driven by automobile exhaust

The absorption driven by automobile exhaust is limited, compared to adsorption. This might be a result of the difficulty in handling the base solution. Javani et al. [7] recycled the exhaust gas through a shell-and-tube heat exchanger, in order to drive the generator, as shown in Fig. 4. The LiBr–water absorption system converts the exhaust heat to cool down the cabin. The cycle is similar to a typical absorption system, where the strong solution absorbs vapor from the evaporator. The water evaporates in the evaporator by taking heat from the cabin, thus providing a cooling effect.

2.3. Absorption system driven by solar energy

In a solar absorption system, the weak solution is regenerated as a solar collector when a film of weak solution flows through the solar panel. The water vapor is evaporated from the weak solution, and the solution become more concentrated and stronger. After regeneration, the cycle can be continued and repeated for evaporation (refrigeration), and/or absorption (dehumidification).

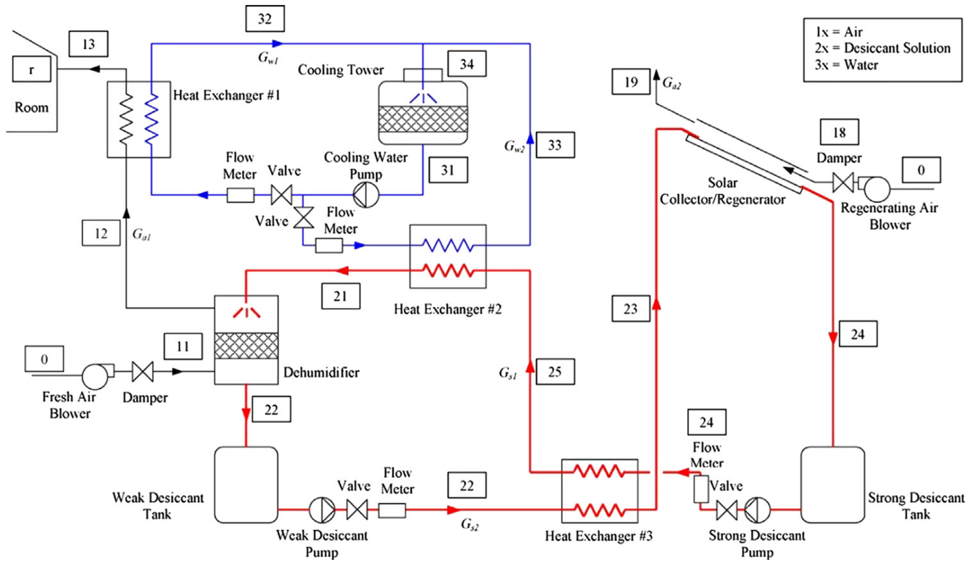

Fig. 5. Open-cycle liquid-desiccant system driven by solar energy [10]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

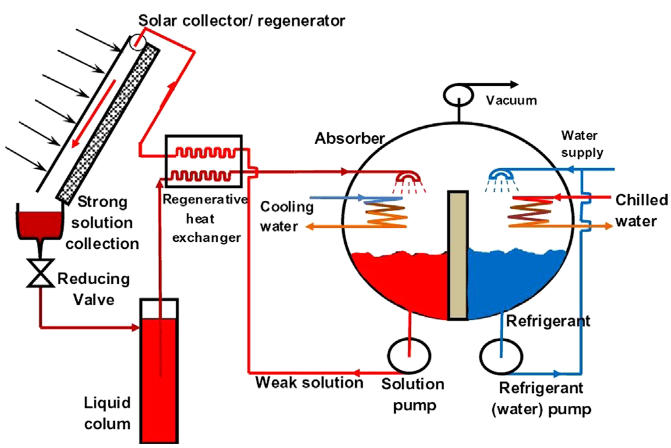

Fig. 6. Weak solution is regenerated at the solar collector [11].

The system/cycle could not proceed if either one of the processes fails (absorption, evaporation, condensation and regeneration). In solar driven absorption, it is normally an open-loop cycle, where the refrigerant is not recycled in a closed loop. A solar absorption system could not operate during nighttime with the disappearance of sunlight. However, solar heat could be stored for the nighttime, or an auxiliary heater could be installed, to cater for demand during the night.

Jakob and Saulich [8] utilized solar energy and waste heat to drive the generator (85 °C) for a small-scale absorption chiller. In this system, the refrigerant is ammonia, and the absorbent is water. As a by-product, the absorption system heats up water from 24 °C to 28 °C, in the absorption and condensation processes. Li and Sumathy [9] described that solar collectors generate the absorption refrigeration (LiBr–water) system. Hot water storage acts as a buffer, and an auxiliary heater acts as a back-up source for the generator. A cooling tower acts as a heat sink for the condenser and absorber. This system provides a chilling effect at the evaporator.

Katejanekarn and Kumar [10] simulated the solar regenerated liquid desiccant system numerically. The weak solution absorbs the humidity (water vapor) from fresh air, and is regenerated by hot air at the solar collector. After regeneration, the strong solution is pumped back to the dehumidifier/absorber, to dehumidify the air. The dehumidified air is cooled down by the cooling tower. The sensible heat is removed by the cooling tower loop (blue), while the latent heat is removed by the absorption loop (red), as shown in Fig. 5. The system is more efficient than the classic system, for the preparation of cool air in a hot and humid country.

Zeiden et al. [11] illustrated a calcium chloride–water liquid desiccant absorption system. The liquid desiccant is weakened by water vapor, and delivered to the solar collector as a weak solution. It then absorbs the heat from the solar collector, the vapor pressure in the weakened solution increases, and water vapor evaporates from the weakened solution. The strong solution is returned to the absorber, and is sprayed to absorb water vapor again. The water vapor evaporates after absorbing heat from the water to be chilled. Water evaporation provides a cooling effect, as shown in Fig. 6. Lychnos and Davies [12] conducted their liquid desiccant experiment powered by solar energy. The strong liquid desiccant removes water vapor from humid air. The weakened solution is regenerated by a solar regenerator. The dry air is cooled down when it evaporates the water falling from the top of the evaporator pad. Finally, the air becomes humid again, and suitable for cooling the greenhouse. Without predrying the air, the air might become overhumid, after it passes through the evaporative pad.

Lizarte et al. [13] make a comparison of the performance of directly air-cooled and indirectly air-cooled LiBr–H_2O absorption chillers. The authors concluded that their directly air-cooled absorption chiller performed better than an indirectly air-cooled LiBr–H_2O absorption chiller. Their thermal coefficient of performance is 0.62 and 0.55.

Gomri [14] developed a computer program for thermodynamic analysis, based on the energy balance, exergy balance, and thermodynamic properties for each reference point. In the single effect lithium bromide absorption system, the auxilliary heater assisted the solar clean energy to regenerate the strong solution, when solar energy is insufficient. The coefficient of performance (COP) is higher when the generator's temperature is 55 °C, and the condenser's temperature is 28 °C. A higher temperature at the generator and condenser will decrease the COP. The exergy performance is also among the highest when the generator's temperature is 55 °C, and the condenser's temperature is 28 °C. The auxilliary heater works harder in the morning and evening, when the solar energy is insufficient.

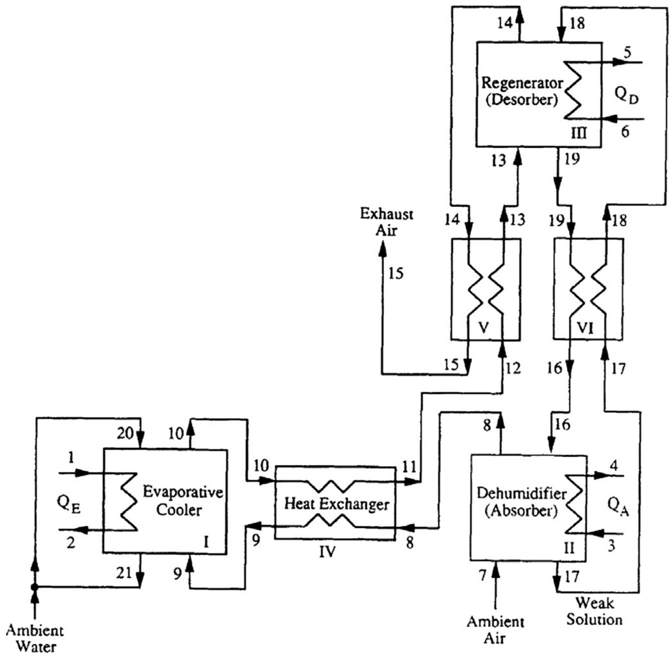

Fig. 7. Open cycled absorption system [17].

Sayadi et al. [15] developed a numerical model, in order to explore the feasibility of implementing an absorption chiller system, using light hydrocarbons as working fluids, in combination with helium as an inert gas. In the system, solar energy and a back-up heat source are available to regenerate the weak solution. At the inlet of the evaporator, helium (as an inert gas) is added, to reduce the partial pressure of the refrigerant. This will provoke evaporation at a low temperature. A cooling tower is included, to cool down the adsorber and condenser. Finally, the cooling effect provided by evaporator will be channeled, to cool down a room.

Said et al. [16] suggested a new, alternative, solar-assisted absorption system, and performed a detailed thermodynamic analysis. They explained the classification of a solar-powered aqua ammonia vapor absorption system, to provide uninterrupted daytime and nighttime cooling. There are three storage facilities required, to support 24 h operation of the liquid absorption cooling system: a cold storage system stores the cold energy generated during the daytime, for use at night; a refrigerant storage system stores the condensed refrigerant during the daytime to cater for nighttime usage; and a heat storage system stores heat energy to heat up the generator during the nighttime. Thus, the absorption process can be continuous.

2.4. Other layout of absorption system

There are other layouts of absorption systems, in order to yield a better coefficient of performance (COP), such as an opened loop absorption circuit, double effect circuit, double stages circuit, etc. Hellmann and Grossman [17] dehumidified the ambient air, and prepared it for an evaporative cooler, where water is evaporated in the dehumidified air flow. During the evaporation process, a cooling capacity of 21.6 kW (Q_E) is created for the chiller (7.2 °C). However, an external heat (Q_D) source is required to desorb the weaken solution. Thus, the COP of the system is defined as a ratio of Q_E to Q_D. This is the open-cycled liquid desiccant, as shown in Fig. 7. Gebreslassie et al. [18] performed exergy analysis for a double-effect series flow, and a double effect parallel flow absorption cycle. In the series flow, the weaken solution (after absorbing water vapor from evaporator) flows directly into the highest temperature generator. After generation, the slightly strong solution will be regenerated into a strong solution at the condenser–generator (CG), while in the parallel flow, the weakened solution is generated concurrently at the higher temperature generator and at the medium temperature generator.

Garousi Farshi et al. [19] conducted exergoeconomins analysis for a double-effect absorption refrigeration system. In their analysis, they considered economics and exergy (thermodynamics) factors, to define an efficient energy conversion system. Garousi Farshi et al. focused on a double-effect absorption system, involving a high pressure generator and a low pressure generator.

Shi and Che [20] proposed a combined power system, with waste heat and liquefied natural gas (LNG) energy. A water–ammonia mixture is desorbed by low temperature waste heat (HX3), while ammonia vapor drives the turbine (T1) and produces power. The strong solution flows to a mixer (absorber) to absorb the ammonia liquid from the condenser pump, while in the LNG loop, LNG is vaporized at the condenser (while ammonia condenses), and drives the turbine (T2).

2.5. Novel absorption mechanism-spray absorber, jet falling absorber and adiabatic

In the absorption system, the cycle starts with a base solution absorbing the refrigerant vapor during the absorption stage. The mechanism of how the two entities (one liquid and one vapor) come into contact, and interact with each other during absorption, will determine how well the whole system performs. Researchers conducted research, to find out which mechanism is a better choice to improve an absorption system.

Venegas et al. [21] described the spray absorber in an adiabatic absorber chamber, using a lithium nitrate–ammonia solution.

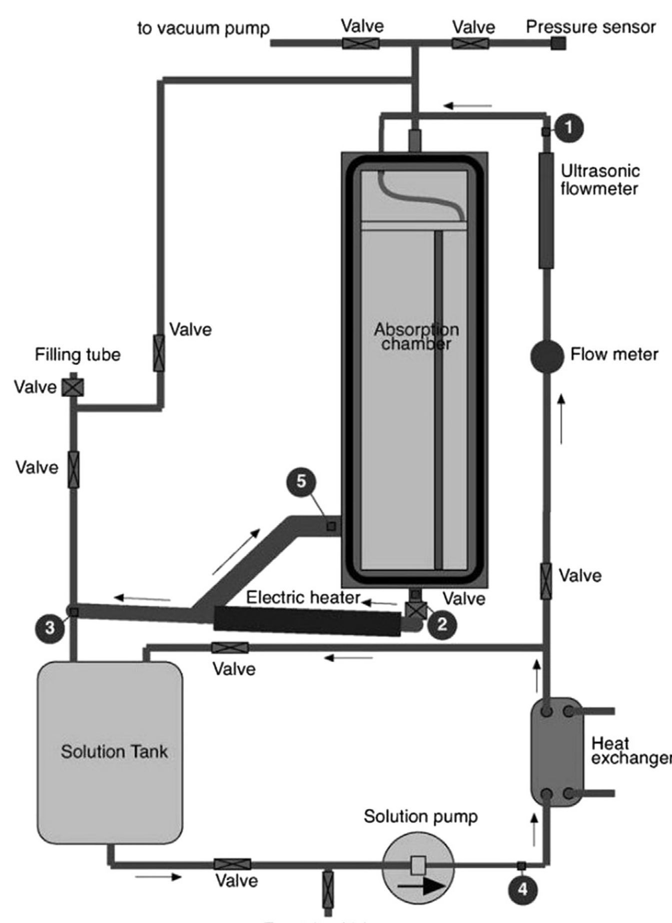

Fig. 8. Jets and falling film increase the efficiency of absorption [23].

The strong, concentrated solution, after precooling in plate-heat exchanger, is sprayed in an adiabatic chamber, in order to absorb the ammonia vapor. By measuring the mass transfer in the absorber chamber, 60% of the absorption process is completed during the deceleration of the drops (strong solution). Niu et al. [22] carried out an experimental study about the falling film of water in a magnetic field, for which ammonia vapor is the refrigerant. They concluded that a magnetic field, in the same direction as the falling film, can enhance the absorption. Arzoz et al. [23] reported an experimental study about the different arrangement of fluid flow in LiBr–water absorption (see Fig. 8). the solution saturated more quickly, and a higher heat coefficient is observed in the arrangement of jet and falling film, rather than droplets.

Ventas et al. [24] studied the adiabatic absorber with a lithium nitrate–ammonia pair. There is an additional subcooler (absorber heat exchanger) compared to a typical absorption system. The effect of the recirculated mass flow in the recirculation loop is studied. Ventas et al. [25] also established a numerical model for the lithium nitrate–water absorption system, and studied the effect of a low pressure booster, fixed between the evaporator and the absorber.

3. Adsorption

In an adsorption system, there are two adsorber beds, with a switching system (between cooling and heating cycle), a condenser, and an evaporator. The cooling or heating circuit for adsorber beds is normally an individual piping of hot gas, hot water and cold water. These pipes lie within the adsorber bed/grains, so only the adsorber grain is in contact with the refrigerant. Unlike absorption, it contains two compartments for absorption and regeneration, and adsorption shares the same adsorber beds, for both the adsorption and regeneration processes. So it takes time for the adsorber bed to cool down for adsorption, and to heat up for regeneration.

3.1. Adsorption system driven by automobile exhaust

In an adsorption system driven by exhaust heat, the exhaust gas passes through the adsorber during desorption. Then, the evaporated refrigerant from the desorber condenses at the condenser. During the adsorption time, the ambient cool air passes through the adsorber, and the refrigerant evaporates from the evaporator to the adsorber.

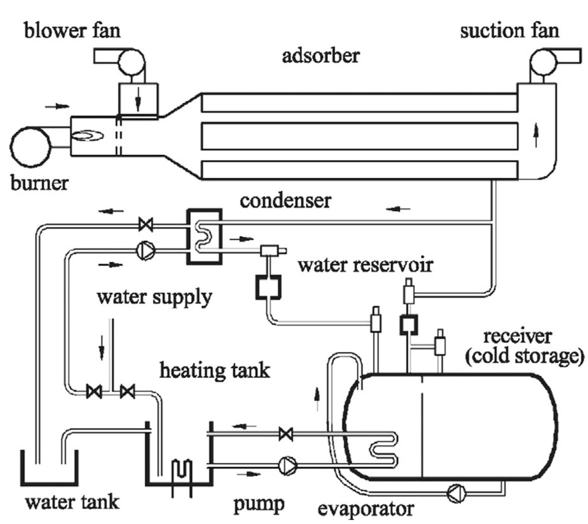

Fig. 9. Adsorption refrigeration driven by automobile exhaust [30].

Wang et al. [26] adapted activated carbon-methanol pair for their exhaust-gas-driven adsorption system. The adsorber and condenser are cooled down by sea water. The desorber is driven by exhaust gas (through a boiler for hot water storage), and a chilling effect is produced at the evaporator. Adsorber bed 1 and adsorber bed 2 take turns to become the adsorber and desorber, in order to provide continuous cooling for the evaporator and ice-maker. The switching of adsorption and desorption for a bed takes place by switching the heat source or cooling source. Before each switching, 1 min of heat recovery, and 2 min of mass recovery process, are required between the two adsorber beds. In the meantime, the refrigerant in the evaporator will be topped up by the condenser.

Grisel et al. [27] adopted silica gel–water in their waste-heat-driven adsorption chilling system. In the water vapor supply line to the adsorber, a demister is placed to prevent water from

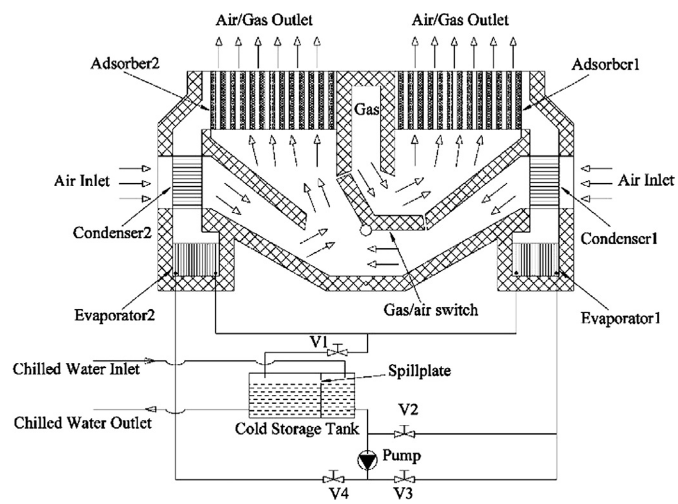

Fig. 10. Gas switch is used to switch between cool air and hot exhaust to the adsorber [33].

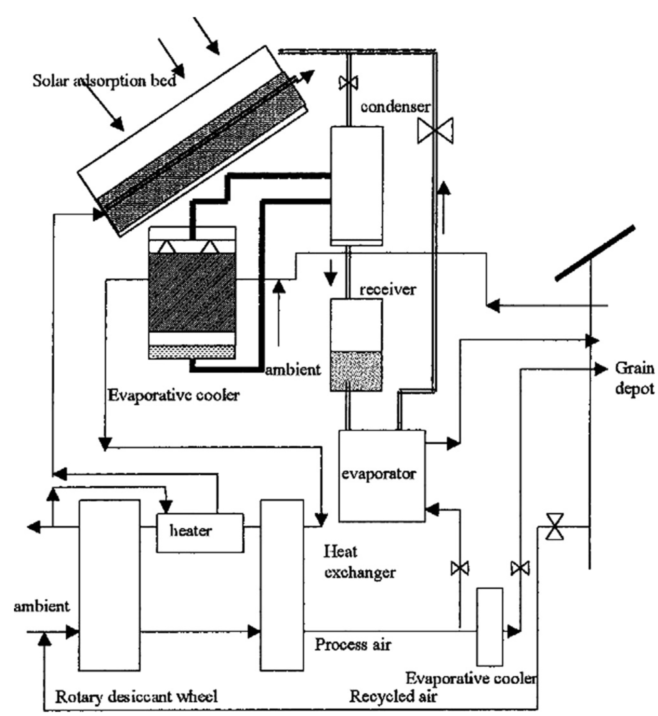

Fig. 11. Household adsorption system driven by solar energy [39].

entering the adsorber. The cooling and heating loop/circuit cool and heat the adsorber bed, while the water/refrigerant is adsorbed and desorbed from the adsorber bed. Wang et al. [28] also conducted an experiment with silica gel–water adsorption. They studied the effect of a variable/fluctuating heat source supply (exhaust gas or solar heat) for the adsorption system.

Lu et al. [29] utilized 140 kg of zeolite and 185 kg of water in their locomotive. The adsorber bed desorbs when exhaust gas flows through the adsorber bed. The water vapor leaves the bed and condenses at an air-cooled condenser. During the adsorption cycle, the exhaust gas exits the chimney, but fresh air is drawn in through the noser inlet. When the vapor pressure is low enough at the adsorber, the evaporator starts to evaporate water vapor for the adsorber. The cooling effect is transferred to the passenger cabin by chilling water. The water not only plays a role as a refrigerant, but also as a sensible cold storage.

Verde et al. [30] adopted Zeolite–water adsorption in their vehicles Heating, Ventilation and Air-Conditioning (HVAC) system for cabin cooling, as presented in Fig. 9. The researchers generate/desorb the adsorber with 80–90 °C engine coolant. The engine coolant is further heated above 90 °C, by recovered heat from exhaust heat. For the adsorption purpose, a reactor cooling loop is prepared. Jiangzhou et al. [31] conducted an experimental study for Zeolite–water adsorption, with a desorption temperature of 200–250 °C. 140 kg of Zeolite and 185 kg of water are able to produce 4.2 kW of cooling power. They utilized exhaust gas and hot coolant to desorb the adsorber (heating loop). The cooling loop will cool down the adsorber during adsorption. Vasta et al. [32] dedicated their research to a mobile adsorption chiller. 4.6 kg adsorbent grains and 60 kg of prototypes' weight could provide 1–2.3 kW of cooling power.

Wang et al. [33] described their adsorption system for a locomotive, as shown in Fig. 10. 350–450 °C of heat source could provide 10 kW of cooling, at 6.5 °C. The adsorbers can be heated up, or cooled down, in 22 min. There is an air switch to control either cooling air to adsorb, or hot gas to desorb the adsorber bed. The bed is connected to the evaporator during adsorption, and is connected to the condenser during desorption. Using a mathematic model, Hu et al. [34] introduced a new composite for the adsorbent bed, which is zeolite/foam aluminum. The water acts as a refrigerant, while the engine exhaust heat drives the adsorption system. The cooling and heating fluid flows alternatively through the tube lying inside the adsorbent bed, during adsorption and desorption. Zhong et al. [35] suggested the Zeolite 13 × –water adsorption cooling system for a truck. The system could reduce environmental emissions, and utilize the waste heat to drive the cabin-cooling system. The adsorption system is driven by a back-up heater when the engine is off.

3.2. Adsorption system driven by solar energy

The availability of solar energy during the daytime allows regeneration/desorption to only take place during the daytime. Desorption occurs concurrently with condensation. The adsorption and evaporation take place concurrently with the cooling of adsorber, during the nighttime. After adsorption, the adsorber is again regenerated by sunlight the next day. In the daytime, solar energy also heats up the water for household usage. Under normal

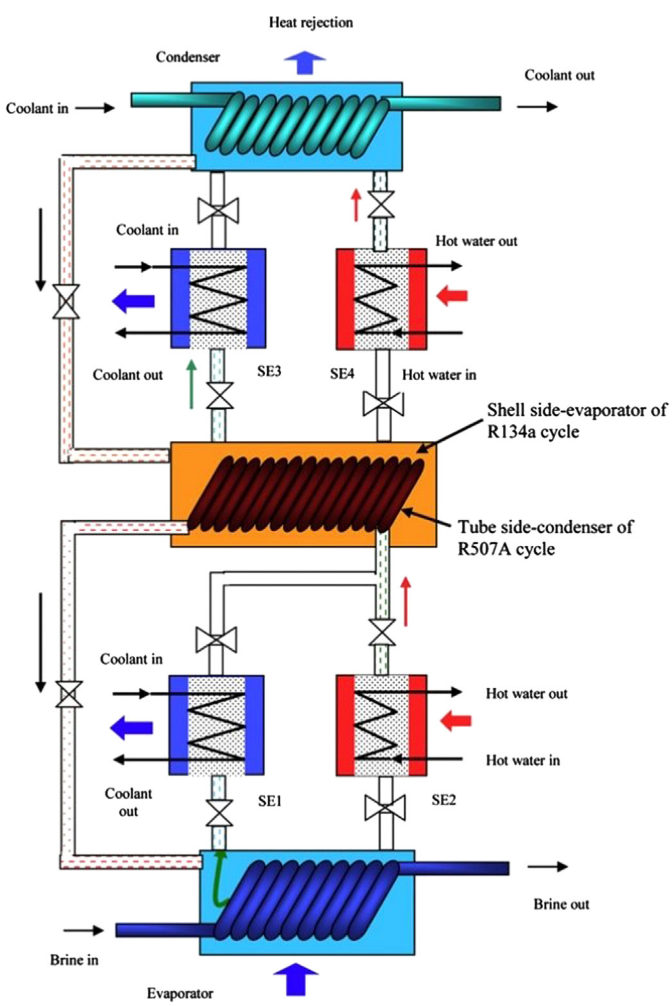

Fig. 12. Combined adsorption system [42].

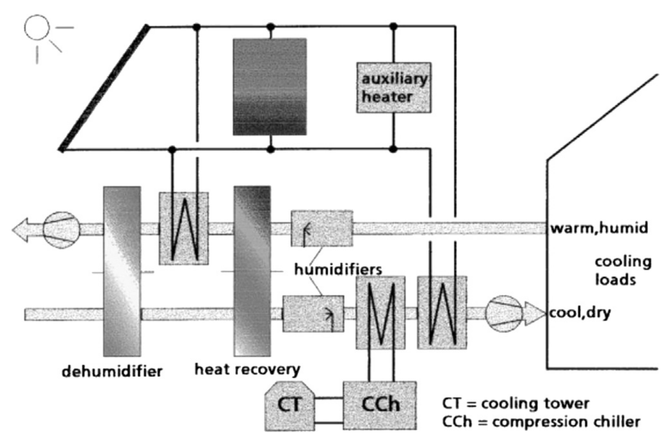

Fig. 13. Solar-driven solid desiccant system [43].

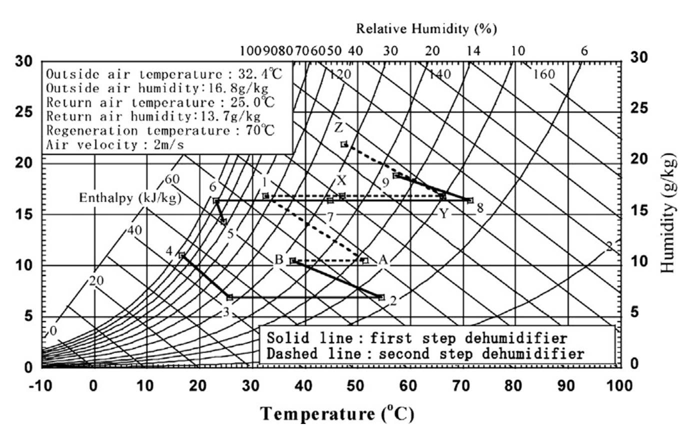

Fig. 14. Humidity and temperature chart for adsorption–dehumidification system [45].

circumstances, the adsorption driven by solar energy provides refrigeration or cooling during the nighttime. However, refrigeration during the nighttime could be kept in cold storage for daytime use. Alternatively, the solar heat could be stored for desorption during the night, and provides cooling during the day.

Wang et al. [36] described their setup of a solar adsorber, inside a water tank driven by a solar collector. In the daytime, solar energy is collected by a solar collector, and heats up the water in a water tank. The hot water then desorbs the adsorber. In the evening, 60 kg of hot water is drained out, and replaced by cold water (or cools down naturally as night falls). When the adsorber is cooled, evaporation cooling happens, and produces 10 kg of ice.

Zhang et al. [37] introduced zeolite-water in their solar adsorption system. During the day, the solar adsorber with zeolite receives solar heat and releases water vapor to the condenser (valves 2 and 3 are closed). The water vapor from the solar absorber is ejected at a fast speed in the ejector, and creates a low pressure area, into which water vapor from the evaporator is pulled (valve 3 is opened). The water vapor is condensed, after being compressed by a diffuser, to the condensation temperature and pressure. In the afternoon, the water is released from the water tank, in order to provide hot water for household usage (by adsorbing heat from the adsorber), and to cool down the adsorber. When the absorber's temperature and pressure decrease to the evaporation state, evaporation starts in the evaporator.

Dai et al. [38] illustrated their adsorption system to enhance the ventilation in a room, with both the cooling cavity driven by solar adsorption, and with the solar chimney. The water tank is cooled by adsorption cooling at night. However the cooling effect is stored in an insulated water tank, to be used during the daytime. During the day, solar energy heats up the air in the solar chimney (RHS), and a cooling cavity cools down the air, in order to provoke ventilation in the room. The hot air (with lower density) moves upwards, while the cold air (with higher density) moves downward. Also, the air path between the solar adsorber and the glass provides a chimney effect with solar heat (LHS) in the daytime. At night, the remaining heat at the solar adsorber and solar chimney continues the chimney effect.

Dai et al. [39] illustrated activated a carbon-methanol pair in their solar adsorption system (see Fig. 11). In the daytime, the solar heat/heater desorbs methanol from the adsorption bed, and condenses the methanol at the condenser (which is cooled down with cold water from the evaporative cooler). At nighttime, the adsorption bed cools down until vapor pressure in the evaporator

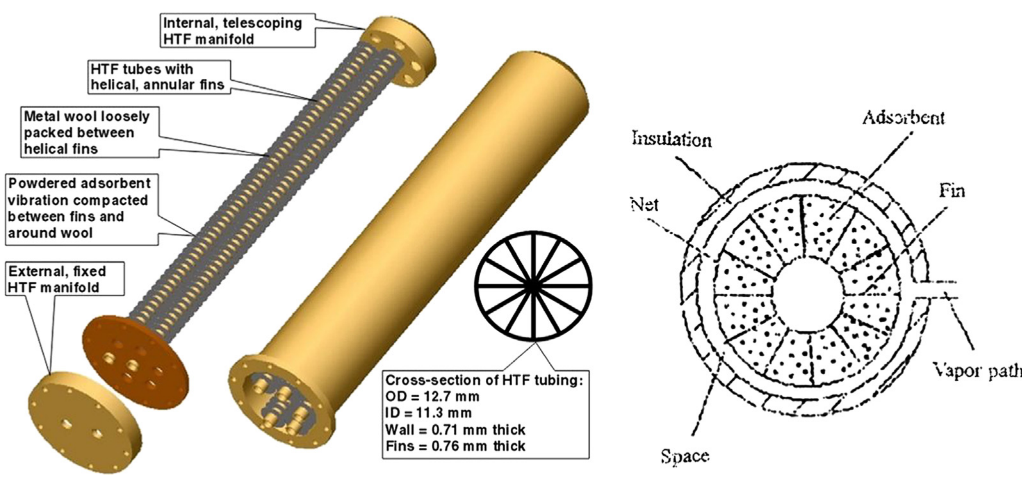

Fig. 15. Detailed construction of an adsorber for adsorption [48].

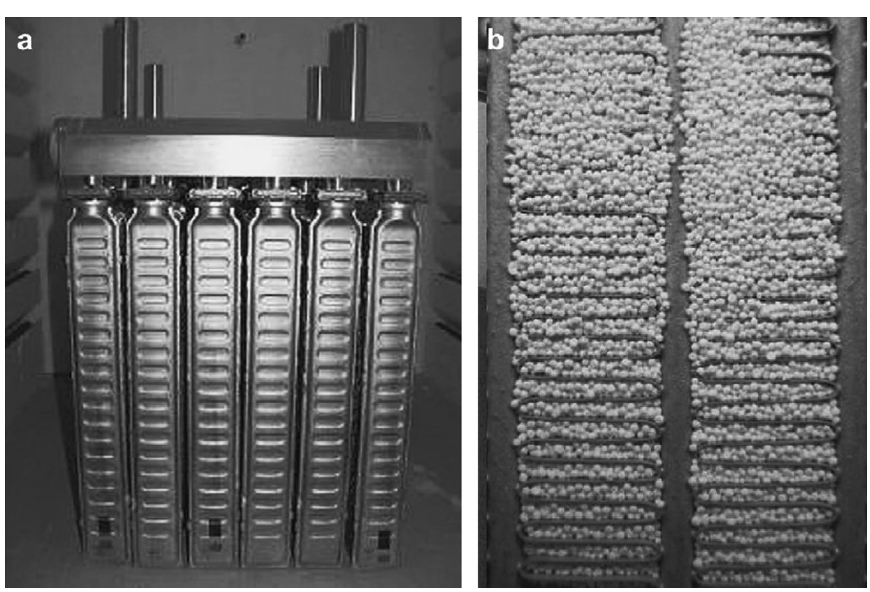

Fig. 16. Adsorber heat exchanger filled with adsorber grains [32].

exceeds the pressure in the adsorber. Thus, the methanol evaporates, and provides cooling in the evaporator. The ambient air is dehumidified by a rotary desiccant wheel, and is cooled by either an evaporative cooler or an evaporator. The rotary desiccant wheel is regenerated by a regeneration loop, which recycles air passing through the evaporative cooler, heat exchanger, heater, and rotary desiccant wheel.

3.3. Other layout of adsorption system

The basic adsorption system for a continuous cooling effect consists of two units of adsorber beds. However, researchers conducted their adsorption research innovatively with three-bed, four-bed, and combined adsorption systems. Jribi et al. [40] suggested the pairing of activated carbon and R1234ze (E) in their mathematic modeling of a four-bed adsorption system. 80 kg of activated carbon, with an 85 °C heat source (hot coolant or exhaust gas), could produce 2 kW of cooling power. Thus, it is suitable for automobile application. It is a four-bed system, where the adsorption beds heat up and cool down in a synchronized manner.

Saha et al. [41] suggested a three-bed adsorber for pairing between activated silica gel and water. The driving heat source varied between 65 and 90 °C. A computer program was established, to study the effect of operating temperature on cooling capacity and the coefficient of performance (COP). Habib et al. [42] established a mathematic model for their combined adsorption system (see Fig. 12). There are two adsorption cycles, and their refrigerants are R134a and R507a, respectively. Two individual cycles are combined, and share a common condenser or evaporator (evaporator for R134a, and condenser for R507a).

Table 1
List of experiments and numerical studies, which have been conducted for absorption.

Authors	Functions	Absorbent/ refrigerant	Power/working temperature	Special remarks
Jeong et al. [1]	Numerical study. To recover the waste heat (for evaporation), to drive the generator with driving steam and finally can heat up the hot water from 30 °C to 60 °C (in absorption and condensation).	Lithium bromide/Water vapor evaporated in evaporator	Generator (95–135 °C, 30380 Pa) absorber (30–60 °C, 2570 Pa) condenser (30–60 °C, 30380 Pa) evaporator (23–38 °C, 2570 Pa)	Recover waste heat for evaporation. Generator is driven by driving steam.
Jakob and Saulich [8]	Performance analysis. To recover solar heat and waste heat (85 °C) to drive the generator and to provide cooling capacity in evaporator.	Water/ammonia	Generator (78–85 °C) absorber (24–29 °C) condenser (24–29 °C) evaporator (6–12 °C) cooling capacity is 12 kW.	Recover waste heat for generator (70–120 °C).
Katejanekarn and Kumar [10]	Experimental study. To dehumidify the air (remove latent heat) by absorption loop and to cool the air (remove sensible heat) by cooling tower. The absorbent absorbs humidity of air and is regenerated (release humidity) at solar collector.	Lithium chloride/ Water vapor in air	–	Open cycle
Hellmann and Grossman [17]	Performance analysis. To operate the chiller by evaporate the water in a flow of dehumidified air. The absorbent is regenerated by external heat source.	Lithium bromide/water vapor in air	Generator (45.8 °C) absorber (29.4 °C) evaporator (7.2 °C) chiller's cooling capacity is 21.6 kW.	Open cycle
Ma et al. [2]	Experimental study. To drive generator and evaporator with steam stripping vapor from rubber plant. Finally the absorber heat up the hot water from 95 °C to 110 °C.	Lithium bromide/water	Generator (98 °C) absorber (95–110 °C) condenser (28–30 °C) evaporator (98 °C) heat flow of 5000 kW	Recover waste heat (98 °C) for evaporator and generator in order to heat water at absorber.
Arzoz et al. [23]	Experimental study	Lithium bromide/water vapor in air	–	Jets and falling film, adiabatic
Ventas et al. [24]	Numerical study	Lithium nitrate/ ammonia	absorber (30 °C) condenser (30 °C) evaporator (8 °C) generator (55–90 °C)	Adiabatic, recycled loop
Venegas et al. [21]	Experimental study	Lithium nitrate/ Ammonia	–	Adiabatic, Spray absorber
Ventas et al. [25]	Numerical study	Lithium nitrate/ Ammonia	Absorber (30 °C) condenser (30 °C) evaporator (8 °C) generator (55–90 °C)	Compression booster
Niu et al. [22]	Experimental study	Water/ammonia	Liquid desiccant temperature (25–28.8 °C)	Falling film and magnetic field
Bassols et al. [3]	Performance analysis	Water/ammonia	Evaporator (−23 °C)	Power Plant ARP produced 1400 kW of refrigeration while CRP produced in seven compressors with 500 kW of refrigeration each.
Bruno et al. [4]	Performance analysis	Lithium bromide/Water	Evaporator (6.7–12.2 °C)	Microgas turbine (MGT)
Liao et al. [6]	Experimental study	Lithium bromide/Water	Generator (280–320 °C) absorber (25–35 °C) condenser (25–35 °C) evaporator (8 °C)	Cogeneration of power and heat for absorption chillers. Methods to prevent crystallization

3.4. Adsorption and solid desiccant

Adsorption could benefit humans as it could act as solid desiccant. Of course, the refrigerant for the adsorption in dehumidification is water vapor. The main purpose is to remove the water vapor in the atmosphere, and reduce the moisture level. After adsorption, the adsorption rotor is concentrated with water vapor, so it needs to regenerate the adsorber rotor by heating. During regeneration, the water vapor is removed from the rotor. The desiccant rotor could be regenerated by an electric heater or solar collector. The temperature and humidity of incoming air (into the indoors) are altered accordingly, passing through a desiccant rotor, heat exchanger, humidifier, and chiller. Finally, the system will provide the room with air of a suitable temperature and humidity. A solid desiccant system will provide dry and cool air for people in a hot and humid country.

Adsorption desiccant is another application of solid adsorption. Some of the system implemented solid adsorption, for both adsorption cooling and adsorption dehumidification. Henning et al. [43] illustrated their research in a dehumidifier wheel system, as shown in Fig. 13. Before the air is supplied to the room, the fresh air is dehumidified by a dehumidifier wheel, precooled by a heat exchanger, humidified by humidifiers, and either cooled by a chiller (during the summer), or heated by a solar-driven heater (during the winter). There is a back-up heater for the solar-driven heater system. Before releasing the air to the atmosphere, the return air from the room is humidified by a humidifier, heated by a heat exchanger, further heated by a solar-driven heater, and humidified by a desiccant wheel. Thus, the return air helps to precool the entering air, and regenerates the desiccant wheel with the assistance of the heater. The system could provide air at a comfortable humidity level and temperature (either hot or cold).

Table 2
List of experiments and numerical studies, which have been conducted for adsorption.

Authors	Research type	Adsorbent and refrigerant	Power/working temperature	Special remarks
Jiangzhou et al. [31]	Experimental study	Zeolite (140 kg) and water (185 kg)	Generator (200–250 °C) condenser (70–80 °C) adsorber (85–110 °C) evaporator (3–5 °C) Locomotive cooling of 4.2 kW	Locomotive
Wang et al. [26]	Experimental study	Activated carbon/methanol	Evaporator (−9 °C) cooling power of 1.9 kW is produced by 2 unit of 60 kg adsorbent bed.	Recover exhaust heat to provide chilling for fishing boat.
Wang et al. [28]	Experimental study	Silica gel/water	Generator (75 °C) adsorber (30 °C) Cooling capacity is 7 kW.	Study the effect of variable heat input towards the system.
Verde et al. [30]	Experimental study	Zeolite/water	Generator (80–90 °C) condenser (35 °C) evaporator (10 °C) Cooling capacity is 5 kW.	Engine waste heat to drive vehicles' air-conditioning system.
Vasta et al. [32]	Experimental study	Zeolite/water	Generator (90 °C) condenser (28–35 °C) adsorber (28–35 °C) evaporator (8–14 °C)	Recovered low-grade heat from engine coolant loop for mobile air conditioner.
Wang et al. [33]	Experimental study	Zeolite/water	Generator (350–450 °C) condenser (60 °C) adsorber (97 °C) evaporator (6.5 °C)	Locomotive
Hu et al. [34]	Numerical study	Zeolite-foam aluminum/water	Generator (300 °C) condenser (40 °C) adsorber (50 °C) evaporator (10 °C)	Analyze new composite for adsorption driven by engine heat.
Zhong et al. [35]	Numerical study	Zeolite/water	Generator (250 °C) condenser (38 °C) evaporator (7 °C)	
Jribi et al. [40]	Numerical study	Activated carbon/R1234ze(E)	Generator (85 °C) adsorber (30 °C) Cooling power of 2 kW is generated with 80 kg activated carbon.	Four-bed adsorption system.
Saha et al. [41]	Numerical study	Silica gel/water	Generator (60–95 °C) condenser (20–40 °C) adsorber (20–40 °C) evaporator (14 °C)	Three-bed adsorption system.
Habib et al. [42]	Numerical study	Activated carbon/R134a and R507	Generator (55–85 °C) adsorber (30 °C) evaporator (-10 °C) Cooling power of 1.4 kW.	Combined adsorption system.
Wang et al. [36]	Experimental study	Activated carbon/methanol	Generator (85–100 °C) condenser (20–35 °C) adsorber (20–35 °C) evaporator (−10 °C) cooling capacity is 1.5 kW (54 MJ in 10 hrs)	Solar-driven adsorption

Daou et al. [44] presented their work on a desiccant wheel and an evaporative cooling system. This system provides cool air once the outside air is dehumidified by the desiccant wheel, precooled by a heat wheel, and cooled by the evaporative cooler. The return air is precooled by an evaporative cooler, preheated by a heat wheel, further heated by a heater, and humidified by a desiccant wheel (dehumidify/regenerate the wheel). Similarly, Dai et al. [39] described the dehumidify loop, integrated with both the adsorption chiller (evaporator) and the evaporative cooler, for providing cool and dehumidified air. The adsorption cooling system is driven by solar energy. In their research, the return air passes through the evaporative cooler before it is heated by the heat exchanger, further heated by a heater, and humidified by a desiccant wheel.

Ando et al. [45] conducted their study on a double-stage adsorption desiccant system. There are four rotors in the system (two dehumidifiers and two heat exchangers). The entry air is dehumidified twice, precooled twice, and further cooled by an evaporative cooler, before it is provided for air-conditioning. Fig. 14 illustrates the humidity and temperature of incoming air and returned air, which change as the air passes through the processes.

3.5. Novel adsorption mechanism

The construction of adsorber beds is another branch of knowledge. The adsorber might be in a hollow tube form, where the refrigerant will evaporate into the inner tube, and will flow into the condenser during desorption. The heating and cooling source comes from the outer tube [46]. In another scenario, the refrigerant evaporates from the outer tube, while cooling and the heating source occurs in the inner tube [47]. Some fins could be added to the outer tube, in order to enhance adsorption efficiency [48,49].

Leite and Daguenet [46] described how a solar collector collects the solar energy, and heats up the annular cylinder adsorber from the outer diameter. The adsorber, built from activated carbon, desorbs the refrigerant vapor (methanol) into the inner tube of the adsorber. The refrigerant vapor will condense at the condenser. When the adsorber is cooled down, the evaporation cooling will be initiated. Chua et al. [47] displayed the construction of an adsorption chiller of silica gel–water. The cooling water and hot water to desorb and adsorb pass through the adsorber at the inner tube. This denotes how the flowing loop of the refrigerant does not get mixed up with the piping of the cooling and heating medium. For research conducted by Lu et al. [29], the exhaust gas or cooled air passed through the adsorber in an enclosed tube, without contaminating the refrigerant. There is a clearly defined refrigerant passage and a cooling/heating medium passage, so the refrigerant only interacts directly with the adsorber.

Lambert [48] invented a powdered adsorbent, which is compacted around the fins and outer tube (heat exchanger). The increase in the adsorption area (with fin) could increase the adsorption rate. The cooling and heating medium will pass through the inside of the tube, in order to transfer the heat, as shown in Fig. 15. Zhang [49] illustrated the adsorbent located around the fin and the tube. The refrigerant flows in the space outside the adsorbent, while the heat transfer fluid flows inside the inner tube. Vasta et al. [32] dedicated their research to a mobile adsorption chiller. 4.6 kg adsorbent grains and 60 kg of prototype weight provided 1–2.3 kW cooling power, as shown in Fig. 16. Table 1 and Table 2 summarized all the numerical works, experiment works and their significant findings which have been conducted for absorption and adsorption.

4. Conclusion

Liquid absorption systems and solid adsorption systems are excellent technologies to recover low-grade heat for refrigeration and dehumidification purposes. The low-grade heat consisted of industry/household waste heat, automobile exhaust heat, and clean solar heat. In this paper, the experiment modeling and numerical modeling of liquid absorption and solid adsorption systems are revised thoroughly. Liquid absorption is more common in household and industry applications, while solid adsorption systems are suitable for moving automobiles, owing to the limitations of liquid handling. With the recycling of waste heat and the utilization of clean solar energy, human dependence on decaying fossil fuel will reduce. Among all the research, absorption and adsorption, driven by clean solar energy, has attracted the most attention in recent years, and will continue to do so in the near future. Finally, it is important to consider the economical aspects, and the feasibility of implementing this technology for mass production.

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References

[1] Jeong S, Kang B, Karng S. Dynamic simulation of an absorption heat pump for recovering low grade waste heat. Applied Thermal Engineering 1998;18(1):1–12.
[2] Ma X, Chen J, Li S, Sha Q, Liang A, Li W, et al. Application of absorption heat transformer to recover waste heat from a synthetic rubber plant. Applied Thermal Engineering 2003;23(7):797–806.
[3] Bassols J, Kuckelkorn B, Langreck J, Schneider R, Veelken H. Trigeneration in the food industry. Applied Thermal Engineering 2002;22(6):595–602.
[4] Carles Bruno J, Valero A, Coronas A. Performance analysis of combined microgas turbines and gas fired water/LiBr absorption chillers with post-combustion. Applied Thermal Engineering 2005;25(1):87–99.
[5] Liu X, Geng K, Lin B, Jiang Y. Combined cogeneration and liquid-desiccant system applied in a demonstration building. Energy and Buildings 2004;36(9):945–53.
[6] Liao X, Radermacher R. Absorption chiller crystallization control strategies for integrated cooling heating and power systems. International Journal of Refrigeration 2007;30(5):904–11.
[7] Javani N, Dincer I, Naterer GF. Thermodynamic analysis of waste heat recovery for cooling systems in hybrid and electric vehicles. Energy 2012;46(1):109–16.
[8] Jakob U, Saulich S. Development and investigation of solar cooling systems based on small-scale sorption heat pumps. Paper presented at the 1st International Congress on Heating, Cooling and Buildings, Lisbon, Portugal; 2008.
[9] Li Z, Sumathy K. Technology development in the solar absorption air-conditioning systems. Renewable and Sustainable Energy Reviews 2000;4(3):267–93.
[10] Katejanekarn T, Kumar S. Performance of a solar-regenerated liquid desiccant ventilation pre-conditioning system. Energy and Buildings 2008;40(7):1252–67.
[11] Zeidan ESB, Aly AA, Hamed AM. Modeling and simulation of solar-powered liquid desiccant regenerator for open absorption cooling cycle. Solar Energy 2011;85(11):2977–86.
[12] Lychnos G, Davies PA. Modelling and experimental verification of a solar-powered liquid desiccant cooling system for greenhouse food production in hot climates. Energy 2012;40(1):116–30.
[13] Lizarte R, Izquierdo M, Marcos JD, Palacios E. Experimental comparison of two solar-driven air-cooled LiBr/H2O absorption chillers: indirect versus direct air-cooled system. Energy and Buildings 2013;62(0):323–34, http://dx.doi.org/10.1016/j.enbuild.2013.03.023.
[14] Gomri R. Simulation study on the performance of solar/natural gas absorption cooling chillers. Energy Conversion and Management 2013;65:675–81.
[15] Sayadi Z, Ben Thameur N, Bourouis M, Bellagi A. Performance optimization of solar driven small-cooled absorption–diffusion chiller working with light hydrocarbons. Energy Conversion and Management 2013;74:299–307.
[16] Said SAM, El-Shaarawi MAI, Siddiqui MU. Alternative designs for a 24-h operating solar-powered absorption refrigeration technology. International Journal of Refrigeration 2012;35(7):1967–77, http://dx.doi.org/10.1016/j.ijrefrig.2012.06.008.
[17] Hellmann HM, Grossman G. Simulation and analysis of an open-cycle dehumidifier–evaporator–regenerator (DER) absorption chiller for low-grade heat utilization. International Journal of Refrigeration 1995;18(3):177–89.
[18] Gebreslassie BH, Medrano M, Boer D. Exergy analysis of multi-effect water–LiBr absorption systems: from half to triple effect. Renewable Energy 2010;35(8):1773–82.

[19] Garousi Farshi L, Mahmoudi S, Rosen M, Yari M, Amidpour M. Exergoeconomic analysis of double effect absorption refrigeration systems. Energy Conversion and Management 2013;65:13–25.
[20] Shi X, Che D. A combined power cycle utilizing low-temperature waste heat and LNG cold energy. Energy Conversion and Management 2009;50(3):567–75.
[21] Venegas M, Rodríguez P, Lecuona A, Izquierdo M. Spray absorbers in absorption systems using lithium nitrate–ammonia solution. International Journal of Refrigeration 2005;28(4):554–64.
[22] Niu XF, Du K, Xiao F. Experimental study on ammonia–water falling film absorption in external magnetic fields. International Journal of Refrigeration 2010;33(4):686–94.
[23] Arzoz D, Rodriguez P, Izquierdo M. Experimental study on the adiabatic absorption of water vapor into LiBr–H_2O solutions. Applied Thermal Engineering 2005;25(5):797–811.
[24] Ventas R, Lecuona A, Legrand M, Rodríguez-Hidalgo M. On the recirculation of ammonia–lithium nitrate in adiabatic absorbers for chillers. Applied Thermal Engineering 2010;30(17–18):2770–7.
[25] Ventas R, Lecuona A, Zacarías A, Venegas M. Ammonia–lithium nitrate absorption chiller with an integrated low-pressure compression booster cycle for low driving temperatures. Applied Thermal Engineering 2010;30(11):1351–9.
[26] Wang L, Wang R, Wu J, Wang K, Wang S. Adsorption ice makers for fishing boats driven by the exhaust heat from diesel engine: choice of adsorption pair. Energy Conversion and Management 2004;45(13):2043–57.
[27] Grisel RJH, Smeding SF, Boer R. Waste heat driven silica gel/water adsorption cooling in trigeneration. Applied Thermal Engineering 2010;30(8–9):1039–46.
[28] Wang D, Wang Y, Zhang J, Tian X, Wu J. Experimental study of adsorption chiller driven by variable heat source. Energy Conversion and Management 2008;49(5):1063–73.
[29] Lu Y, Wang R, Jianzhou S, Xu Y, Wu J. Practical experiments on an adsorption air conditioner powered by exhausted heat from a diesel locomotive. Applied Thermal Engineering 2004;24(7):1051–9.
[30] Verde M, Cortés L, Corberán J, Sapienza A, Vasta S, Restuccia G. Modelling of an adsorption system driven by engine waste heat for truck cabin A/C. Performance estimation for a standard driving cycle. Applied Thermal Engineering 2010;30(13):1511–22.
[31] Jiangzhou S, Wang R, Lu Y, Xu Y, Wu J, Li Z. Locomotive driver cabin adsorption air-conditioner. Renewable Energy 2003;28(11):1659–70.
[32] Vasta S, Freni A, Sapienza A, Costa F, Restuccia G. Development and lab-test of a mobile adsorption air-conditioner. International Journal of Refrigeration 2012;35(3):701–8.
[33] Wang D, Xia Z, Wu J. Design and performance prediction of a novel zeolite–water adsorption air conditioner. Energy Conversion and Management 2006;47(5):590–610.
[34] Hu P, Yao J-J, Chen Z-S. Analysis for composite zeolite/foam aluminum–water mass recovery adsorption refrigeration system driven by engine exhaust heat. Energy Conversion and Management 2009;50(2):255–61.
[35] Zhong Y, Fang T, Wert KL. An adsorption air conditioning system to integrate with the recent development of emission control for heavy-duty vehicles. Energy 2011;36(7):4125–35.
[36] Wang R, Li M, Xu Y, Wu J. An energy efficient hybrid system of solar powered water heater and adsorption ice maker. Solar Energy 2000;68(2):189–95.
[37] Zhang X, Wang R. A new combined adsorption–ejector refrigeration and heating hybrid system powered by solar energy. Applied Thermal Engineering 2002;22(11):1245–58.
[38] Dai Y, Sumathy K, Wang R, Li Y. Enhancement of natural ventilation in a solar house with a solar chimney and a solid adsorption cooling cavity. Solar Energy 2003;74(1):65–75.
[39] Dai Y, Wang R, Xu Y. Study of a solar powered solid adsorption–desiccant cooling system used for grain storage. Renewable Energy 2002;25(3):417–30.
[40] Jribi S, Saha BB, Koyama S, Chakraborty A, Ng KC. Study on activated carbon/HFO-1234ze (E) based adsorption cooling cycle. Applied Thermal Engineering 2013;50(2):1570–5.
[41] Saha B, Koyama S, Lee J, Kuwahara K, Alam K, Hamamoto Y, et al. Performance evaluation of a low-temperature waste heat driven multi-bed adsorption chiller. International Journal of Multiphase Flow 2003;29(8):1249–63.
[42] Habib K, Saha BB, Chakraborty A, Koyama S, Srinivasan K. Performance evaluation of combined adsorption refrigeration cycles. International Journal of Refrigeration 2011;34(1):129–37.
[43] Henning HM. Solar assisted air conditioning of buildings–an overview. Applied Thermal Engineering 2007;27(10):1734–49.
[44] Daou K, Wang R, Xia Z. Desiccant cooling air conditioning: a review. Renewable and Sustainable Energy Reviews 2006;10(2):55–77.
[45] Ando K, Kodama A, Hirose T, Goto M, Okano H. Experimental study on a process design for adsorption desiccant cooling driven with a low-temperature heat. Adsorption 2005;11:631–6.
[46] Leite APF, Daguenet M. Performance of a new solid adsorption ice maker with solar energy regeneration. Energy Conversion and Management 2000;41(15):1625–47.
[47] Chua H, Ng K, Malek A, Kashiwagi T, Akisawa A, Saha B. Modeling the performance of two-bed, sillica gel–water adsorption chillers: Modélisation de la performance des refroidisseurs ą deux lits ą adsorption utilisant le gel de silice/eau. International Journal of Refrigeration 1999;22(3):194–204.
[48] Lambert MA. Design of solar powered adsorption heat pump with ice storage. Applied Thermal Engineering 2007;27(8):1612–28.
[49] Zhang L. A three-dimensional non-equilibrium model for an intermittent adsorption cooling system. Solar Energy 2000;69(1):27–35.